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A macro-modelling approach for the analysis of infilled frame structures

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Abstract

An approach towards the assessment of the in-plane horizontal capacity of infilled frames consists of the substitution of each infill with an equivalent diagonal strut. While several studied have been focused on the in-plane horizontal behavior of full infills, limited work has been carried out to investigate the behavior of infills with openings. Also, in most of the studies, the influence of the vertical load is not present. In this paper, an approach for the identification of an equivalent strut which takes into account the effects of the openingat the infill is presented. An extended FE analysis considering the infilled frames containing different sizes of opening under various amounts of vertical loads have been developed. The model is used to identify the mechanical characteristics of an equivalent strut. From the results analysis, a relationship between the width of an equivalent strut and the reduction coefficient (λ^*) representing the mechanical characteristics of frame and infill has been obtained.

Keywords: Infilled frames, equivalent strut, masonry, FE analysis

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1. Introduction

Infill walls subjected to lateral loads are radically affecting the behaviour of infilled framed structures under lateral loads(Stafford Smith 1968, Stafford Smith and Carter 1969, Cavaleri et al. 2005, Asteris et al. 2003, Asteris et al. 2011, Wang et al. 2011, Willam et al. 2010, Yang et al. 2010, Sarhosis et al. 2014). The stiffness and strength variation of an in-filled frame depends on the geometrical and mechanical properties of the masonry infill wall and surrounding frame;the frame to masonry infill wall stiffness ratio as well as the interaction between the infill panel and the surrounding frame. Among these factors the level of vertical load transferred from the frame to the infill and the presence of openings have to be considered (e.g. NCEER 1994) in the analysis.

For the analysis of the masonry infill frames, the macro-modelling approach, which replaces the infill with one or more equivalent struts have extensively been used in the past by various researchers including Asteris (2003), Cavaleri and Papia (2003), Crisafulli and Carr (2007), Zhai et al. (2011), Chrysostomou and Asteris (2012), Moghaddam and Dowling (1987) and Asteris et al. (2011). However, as far as the authors' knowledge is concerned, there are limited studies on the influence of the combination of vertical and horizontal loads on the masonry in-fills containing openings.

Stafford & Smith (1968) investigated the influence of a uniformly distributed vertical load observing a considerable increase in the lateral stiffness and lateral strength. More recently, Papia et al. (2004) studied the mechanical behaviour of RC frames infilled with brick masonry wallsand observed a similar effect. Also, Stafford & Smith (1968) and Valiasis & Stylianidis (1989) considered the vertical load effect to be conservative and did not take it into account, among the variables affecting, the evaluation of the cross-section of the equivalent strut. Nevertheless, while this conclusion can be valid for a single frame, it may not be conservative for complex structures with such as partially infilled frame structures.

Also, according to Mosalam et al. (1997) and Holmes (1961), infill panels containing openings will normally characterised by a reduced stiffness and strength when compared to the full infill panels. The effect of openings on the masonry infill panels have also been studied experimentally. In 1971, Mallick and Garg (1971) carried out studies on the position of the opening. Next year, Liauw (1972) undertook several experiments and formulated a simplified model, Also, Schneider et al. (1998) investigated the case of large windows on the behaviour of infilled steel frames. More recently, Kakaletsis and Karayannis (2007) conducted an experimental program to investigate the effect of window and door openings on the hysteretic characteristics of infilled RC frames and understand the relative merits of the position of thewindow and door openings in the frame. Furthermore, Kakaletsis and Karayannis (2008, 2009) and Kakaletsis (2009) investigated experimentally the compressive strength, themodes of failure, the stiffness and the energy dissipation of infilled RC frames containing openings and subjected to cyclic loading. Moreover, Mosalam et al. (1997) carried out a series of experimental tests on gravity load–designed steel frames with semi-rigid connections infilled with unreinforced masonry walls subjected to cyclic lateral loads. The experimental tests were conducted to evaluate the effects of the relative strength of the concrete blocks and mortar joints, the number of bays, and the opening configuration of the infill on the performance of single-story reduced-scale infilled frames. A simple iterative FEM model was proposed by Achyutha et al. (1986) to investigate the infilled frames containing openings with or without stiffeners around the openings. From the results, it was found that when the percentage of window opening is greater than 50%, the contribution of the infill panels can be neglected. Asteris (2003) proposed graphs to estimate the stiffness-reduction factor corresponding to the size and location of the opening. The analytical results demonstrated that for the samples considered, a 20–30% opening reduces the stiffness of the solid-infilled frame by about 70–80%. Tasnimi and Mohebkhah (2011) studied the behaviour of steel frames with masonry-infill panels by examining six full-scale one-story, one-bay specimens with central openings. Cyclic tests demonstrated that partially infilled frames do not always increase the ductility of the frames, since ductility depends on the failure mode of the infill material. Moreover, a relation to determine the equivalent strut's width- reduction factor has been proposed.

The effects of openings on stiffness and strength of infilled frames are primarily taken into consideration by reduction factors (Tasnimi and Mohebkhah 2011; Al-Chaar et al. 2003; Al-Chaar 2002; New Zealand Society for Earthquake Engineering 2006; Durrani and Luo 1994; Mondal and Jain 2008; Asteris 2003, Papia et al. 2003). The reduction factor shows the ratio of stiffness or strength of partially infilled framesto that of a similar solid one. For the aforementioned studies, the contribution of the vertical loads to the strength of the infill wall panels is not taken into account leading to inaccurate results since the influence of vertical load is a critical parameter which affects the contact lengths (Fig. 1) between the infill wall and the surrounding frame.

In this paper, an analytical equation for the determination of the reduction factor of the infill wall (equivalent compressive strut) stiffness taking into account the percentage opening of the infill wall (area of opening to the area of infill wall) as well as the vertical load distribution is proposed. The proposed equation based on similar previous proposal proposed by Asteris (2003) (for taking into account the effect of the openings) and by Amato et al. (2008, 2009) for taking into account the vertical loads. To validate the proposed equation an in-depth analytical investigation using a micro-modelling Finite Element method was conducted. The numerical procedure provides the "exact" response of a series of infilled frames under horizontal and vertical loads by modelling the compressive stress transmitted by the frame to the infill through contact surface elements governed by the Coulomb friction law. The term "exact" is referring to an infill which is modelled by a detailed FE micro-modelling approach and the regions in which frame and infill transmit compressive stress to each other are modelled by contact surface elements.

2. Identification of the width of an equivalent strut

The cross-section of the pin-jointed strut equivalent to an infill (Fig. 2-a) can be obtained by imposing the initial lateral stiffness to be equal to the initial stiffness of the equivalent braced frame (see Fig. 2-b). Denoting $\overline{D}_i$ the stiffness of the actual system (Fig.2-a) solved by the Finite Element Method (micro-modelling approach) and D_i the stiffness corresponds to the simplified model (Fig. 2-b), their equivalence can be written as:

$$D_i = \overline{D}_i \tag{1}$$

The dimensionless value of the lateral stiffness D_i of the infill frame (Fig. 2-b equivalent to Fig. 3-a), , for the case of lateral top displacement $\delta = 1$, is equal to the sum of the dimensionless values of the two horizontal forces D_d, D_f to be applied to the schemes in Fig. 3-b and Fig. 3-c, (obtained as the decomposition of the scheme in Fig.3-a based on the principle of superposition).The dimensionless value of the lateral stiffness D_i of the infill frame is equal to::

$$D_i = D_d + D_f \tag{2}$$

For the scheme in Fig. 3-b the lateral stiffness D_d can be calculated as follows:

$$D_d = \frac{k_d \cos^2\theta}{1 + \frac{k_d}{k_c} sen^2\theta + \frac{1}{4}\frac{k_d}{k_b}\cos^2\theta} \tag{3}$$

where k_d , k_c and k_b are the axial stiffness of the diagonal strut, column and beam respectively:

$$k_d = \frac{E_d\, t\, w}{d}; \quad k_c = \frac{E_f\, A_c}{h'}; \quad k_b = \frac{E_f\, A_b}{\ell'} \tag{4}$$

In Eq. (4), E_d and E_f are the Young's modulus of the infill along the diagonal direction and the Young's modulus of the concrete constituting the frame; t is the thickness of the infill; A_c and A_b are the column and beam cross-sectional areas; the angle θ defines the diagonal direction of the strut and h' and ℓ' are the height and the length of the infill frame (all the above parameters are explained in Fig. 2).

The Young's modulus of the infill along the diagonal can be estimated by combining the masonry elastic moduli along the horizontal and vertical directions as suggested in (Jones 1975), or by using the simplified approach discussed by Cavaleri et al. (2013) on the basis of the experimental studies reported in (Cavaleri et al., 2012).

The lateral stiffness corresponding to the frame D_f (Fig. 3-c), for the case of columns having the same cross-section, can be estimated using the following expression:

$$D_f = K\left[24\,\frac{E_f\,I_c}{h'^3}\left(1-1.5\left(3\,\frac{I_b}{I_c}\,\frac{h'}{\ell'}+2\right)^{-1}\right)\right] \tag{5}$$

where I_c and I_b are the moments of inertia of column and beam sections respectively and K is a constant depending on the aspect ratio of the infill ($K=0.7$ for $\frac{\ell}{h}=1$, $K=0.5$ for $\frac{\ell}{h}=2$). In the case where columns are of different cross-sections, a mean value of their axial stiffness can be used.

2.1 "Exact" infilled frame stiffness

For the evaluation of the lateral stiffness by means of the micro-modelling approach, the FE program SAP 2000 has been used. Both the frame and the infill have been modelled using four node plane stress solid elements assuming elastic, isotropic and homogeneous elastic materials behaviour. The frame-infill interaction have been modeled using interface elements acting only in compression (zero tensile strength). The mechanical characteristics calibrated in such a way to simulate the presence of a mortar having an assigned elastic modulus. The zero tensile strength assumption enables the simulation of the detachment between the frame and the infill. Because the interaction between the frame and the infill is strictly associated with the frame to infill contact length, which is influenced by the vertical load, the model allows the evaluation of the system's lateral stiffness $\overline{D}_i$ in relation to the vertical load.

2.2 Equivalent strut cross-section

By substituting the value of D_i obtained from Eq. (2) in Eq. (1), one obtains:

$$\overline{D}_i = D_d + D_f \tag{6}$$

Furthermore, by substituting Eq.(3) in Eq.(6), the ratio w/d can be expressed as a function of the "exact" lateral stiffness $\overline{D}_i$ of an infilled frame given by the FE model previously described and the bare frame stiffness D_f given in Eq. (5):

$$\frac{w}{d} = \frac{\overline{D}_i - D_f}{E_d\, t\, cos^2\theta}\left(1 - \frac{\overline{D}_i - D_f}{k_c}\left(\frac{h'^2}{\ell'^2} + \frac{1}{4}\frac{k_c}{k_b}\right)\right)^{-1} \tag{7}$$

From eq. (7), the ratio ration of the width of equivalent pin-jointed diagonal strut to the length of the diagonal strut (w/d) can be represented as a function of λ^* , $w/d = f(\lambda^*)$, which can take into account the influence of vertical loads and the size of the openings.

By running a number of simulations for infilled frames characterized by different mechanical and geometrical values and different loading conditions, a set of points representing the global frame-infill behaviour (λ^*) and the characteristics of each equivalent strut (w/d) can be obtained.

In this study, in agreement with the conclusions of Papia et al. (2003) the parameter λ^* has been takenas::

$$\lambda^* = \frac{E_d}{E_f}\frac{t\, h'}{A_c}\left(\frac{h'^2}{\ell'^2} + \frac{1}{4}\frac{A_c}{A_b}\frac{\ell'}{h'}\right) \tag{8}$$

3. Numerical investigation

The numerical analysis was carried out for different values of mechanical and geometrical properties of an infilled frame and for four vertical load levels. For each analysis, the lateral stiffness $\bar{D}_i$ of the system was calculated as the ratio between the applied horizontal load and the inter storey average displacement. The horizontal and vertical forces acting on the frame were applied on the initial and final section of the upper beam at middle depth, while the vertical load was concentrated on the top nodes of the upper beam-column joints. Values of the elastic modulus E_f of the concrete frame were varied from 10,000 to 25,000 MPa while the Poisson's ratio kept constant and equal to ν_f = 0.15. The diagonal elastic modulus E_d was in the range 3,000 to 10,000 MPa and the diagonal Poisson ratio ν_d was equal to 0.2.

The interface elements used to model the interaction between surrounding frame and infill panel were calibrated and an elastic modulus in compression of the mortar equal to 3,000 MPa obtained.

Two different values of the aspect ratio ℓ / h, namely 1 and 2, were investigated. Different dimensions for the openings (centered and homothetic with respect of the boundary of the infill) were considered.

The size of each opening was defined by the dimensionless parameter $\xi = h_v / h = \ell_v / \ell$, h_v and ℓ_v being the dimensions of the opening itself, see Fig.(2).

The analyses were repeated for four dimensionless vertical load levels: $\varepsilon_v = 0$, $\varepsilon_v = 0.00016$, $\varepsilon_v = 0.00032$, $\varepsilon_v = 0.00080$ where ε_v is defined as

$$\varepsilon_v = \frac{F_v}{2A_c E_f} \tag{9}$$

A_c being the mean cross section area of the columns and F_v the total vertical load acting on the frame.

In Figs. 4 &5, the influence of the lateral load and the size of the opening to the contact lengths (beam-infill and column-infill) is clearly depicted. Especially, the greater the opening size, the greater the beam-infill and column-infill contact length. In agreement with previous experimental (Smith 1968) and analytical (Asteris 2003) works, large openings result the curvature of the infill to follow the curvature of the frame. In Fig. 6 the results of the numerical investigation in the case of aspect ratio of infills ℓ / h=1 are inserted showing the correlation between the dimensionless width of the equivalent strut and the parameter λ^* . Fig. 7 refers to the case were ℓ / h equals to2.

From the results analysis, it was found that the effect of vertical loads reduces as the ratio between the dimensions of the opening and the dimensions of the infill increases. This is proved by the fact that for a fixed λ^* , the values of w/d correspond to different levels of the vertical load which tends to become similar. Furthermore, it can be observed that as the area of openings increases, the variation of *w/d* (i.e. λ^*), becomes smaller.

Fig. 8 shows the reduction factor (*r*) of *w/d* against the opening ratio ξ for square infills (ℓ / h=1) and rectangular infills (ℓ / h=2) without vertical loads ($\varepsilon v = 0$). From Fig.8 and for low values of $\xi = h_v / h = \ell_v / \ell$ (i.e. up to 0.2), the ratio ℓ / h have a minimal effect on ………, while for values of ξ greater than 0.2 a reduction of the dimensionless strut width is obtained. Also, for each value of the opening ratio, to a contained range of values for the factor *r* can be obtained. The different values of *r* for assigned ξ correspond to different values of λ^* in the range assigned for this parameter. Considering the contained range of values for *r* for assigned ξ and that this fact is more prevalent for high values of the opening ratio ξ when the reduction of *w/d* is strongly pronounced, that is infills have not more a significant effect on the behaviour of the frame, surely a unique value of *r* can be associated to each value of the opening ratio ξ. On the basis of this consideration, the numerical results can be fitted by the analytical expression:

$$r = 1 + 0.24\xi - 4.23\xi^2 - 2.6\xi^3 + 12.73\xi^4 - 7.15\xi^5 \tag{10}$$

It is important to note that eq. 10 does not depend on the aspect ratio ℓ / h.
In Figs. 9 and 10 the reduction factor of the dimensionless strut width due to openings is combined with the amplification factor (k) due to vertical loads. The numerical results show that it is not possible to add the effects of openings and vertical loads since there is an interaction between the two phenomena which controls the behaviour. As a consequence the resulting amplification/reduction factor is obtained as a nonlinear function of r and k as it will be discussed below.

4. Model for the identification of the equivalent strut

Results of numerical investigations presented here, show that the loss of stiffness due to the openings and the gain of stiffness due to vertical loads can be correlated with the characteristics of an infilled frame (λ^*). The results show that the effects of openings and vertical loads depends on the parameter ξ defining the size of the opening: ξ= hv / h = ℓv / ℓ , the parameter λ^* characterizing the infilled frame and the parameter ε_v characterizing the level of vertical loads defined in Eq.(9). Imposing that the Eq. (7) assumes the form:

$$w / d = r \cdot g'(k) \cdot g''(l / h) \cdot g'''(\lambda^*) \tag{11}$$

where r is the reduction factor $0 < r < 1$ taking the openings in the infills into account, while k is the amplification factor taking the effect of the vertical load into account in absence of openings, the problem is to find an expression for the functions $g'(k), \cdot g''(l / h), g'''(\lambda^*)$. This problem can be solved by observing the results of the numerical investigation.
In Papia et al (2003) it has been proved that the function $g'''(\lambda^*)$ can be expressed as

$$g'''\left(\lambda^*\right) = \frac{c}{\left(\lambda^*\right)^{\beta}} \tag{12}$$

Where

,

$$c = 0.249 - 0.0116\ \nu_d + 0.567\ \nu_d^{\ 2} \tag{13}$$

$$\beta = 0.146 + 0.0073\ \nu_d + 0.126\ \nu_d^{\ 2} \tag{14}$$

The numerical investigation carried out in this work showed that there is a non-linear relationship between the parameters *k* and *r*. , Therefore , the following equation can be used

$$r \cdot g'\left(k\right) \cdot g''(l / h) = rk^{\gamma}\, \frac{h}{\ell} \tag{15}$$

where

$$k = \left[1 + \left(18\lambda^* + 200\right)\varepsilon_v\right] \tag{16}$$

and

$$\gamma = 1 + \frac{0.5r}{(h / \ell)^4} \tag{17}$$

The Eq. (16) for *k* was previously proposed by Amato et al. (2009) for the case of infills without opening and verified for square infilled frame while here it is proposed for square and rectangular infills in general.

In Figs.9-10 it is possible to note as the analytical proposal Eq. (15) fits the numerical results. Eq. (15) takes into account the variation of the dimensionless width due to λ^* for a high value of the opening ratio (i.e. close to 1) and neglects the influence of λ^* for the lowest values of ξ where the influence of the infills themselves becomes negligible.

To this point observe that the strong interaction between openings and vertical loads is expressed by the exponent γ applied to the parameter *k* . In fact, while k was generated to take the influence of vertical loads into account, γ depends on the reduction factor r that, conversely, was generated to take the influence of openings into account. Considering Eqs. (16 &17) allows one to conclude that if the are no vertical loads the following equation is valid:

$$k^{\gamma} = k \tag{18}$$

The above formulation is an extension of the one proposed by Amato et al. (2009).

In Fig.11 the values assumed by k^{γ} varying the vertical loads and the opening ratio can be observed, evidencing vertical loads seems to assume a more strong role in the case of square infills.

The equation (15) for the reduction factor *r* can be considered as an updating of the expression proposed by Asteris (2003), Asteris et al. (2013), Asteris et al. (2012) obtained fromthe FE model. However as concluded by Asteris (2003), the reduction factor *r* here proposed does not depend on the aspect ratio of infills but assumes lightly different values especially for the cases of low levels of the opening ratio.

Asteris (2003) proposed the following expression for the calculation of *r*:

$$r = 1 - 2\alpha_w^{0.54} + \alpha_w^{1.14} \tag{19}$$

where, α_w is the infill wall opening ratio (area of opening to the area of infill wall).

Considering that $\alpha_w = \xi$ eq.(19) can be rewritten as

$$r = 1 - 2\left(\frac{\ell_v h_v}{\ell \cdot h}\right)^{0.54} + \left(\frac{\ell_v h_v}{\ell \cdot h}\right)^{1.14} = 1 - 2(\xi)^{1.08} + (\xi)^{2.28} \tag{20}$$

In Fig. 12, a comparison between the function (10) and the function (20) is presented evidencing that the two proposals converge for the highest values of ξ. Hence, the differences results from the low values of ξ.

Conclusions

The presence of masonry infill wall panels within a framed structure will strongly affect its structural response under horizontal actions and seismic loads. Recent developments have shown that such interaction can be expressed by replacing the characteristics of the panel with that of an equivalent diagonal strut. Also, research has shown that there are several parameters influencing the definition of the diagonal strut and its equivalent width. The latter depends on the degree of coupling between geometrical and mechanical features of the frame and masonry infill.

In this paper, an analytical expression for the identification of the equivalent strut dimensionless width *w/d*, and therefore of its stiffness, has been proposed by means of an extensive numerical investigation which was carried out using a series of FE models representative of the “exact” response. The expression derived involves the product of a reduction factor function $r(\xi)$, where $(0 \leq r(\xi) \leq 1)$, and takes into account the stiffness reduction due to the openings, taking the effect due to vertical load, the infill aspect ratio and the geometrical-mechanical features of the overall system.

A good fit of results obtained between the analytical predictions and the numerical investigation. Also, from the results analysis it was found that::

- The presence of opening strongly reduces the stiffness of the infill panel and this reduction does not depend on the aspect ratio of the infill;
- The greater the opening size, the greater the beam-infill and column-infill contact length
- Vertical loads increase the contact infill-frame lengths, thus increase the overall stiffness of the infill panel;
- The influence of vertical loads is significant for solid infills. In contrast is almostnegligible for infill panels with large openings;The capacity of vertical loads to increase the stiffness is maximum for square infills and it slightly reduces increasing their aspect ratio. From the

analytical results, it was found that all the functions composing the final expression of *w/d* are not independent one by each other and moreover their combination is nonlinear. This should be interpreted as natural consequence of st*ron*g coupling affecting the infill-frame interaction mechanic.

The proposed expression is a reliabletool for the determination of equivalent compressive pin jointed strut width since it simultaneously accounts for a large number of paramters not generally accounted for by already available models in the literature. The proposed expression is also increasing predictive accuracy and reliability of the analysis.

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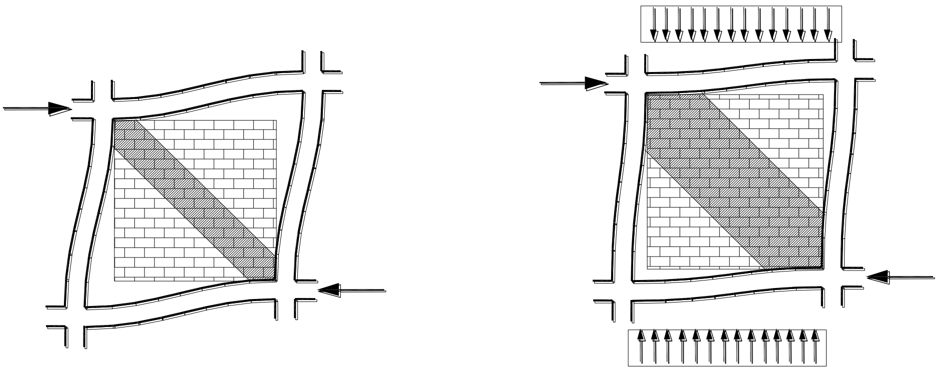
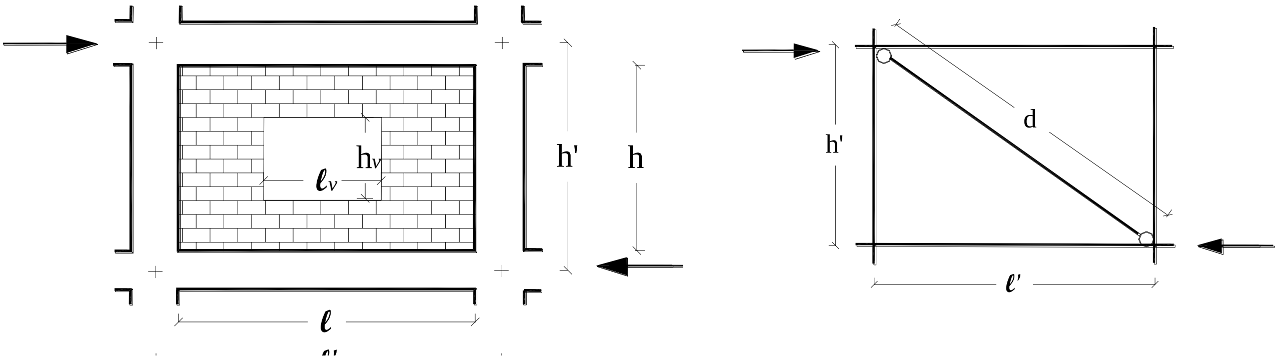
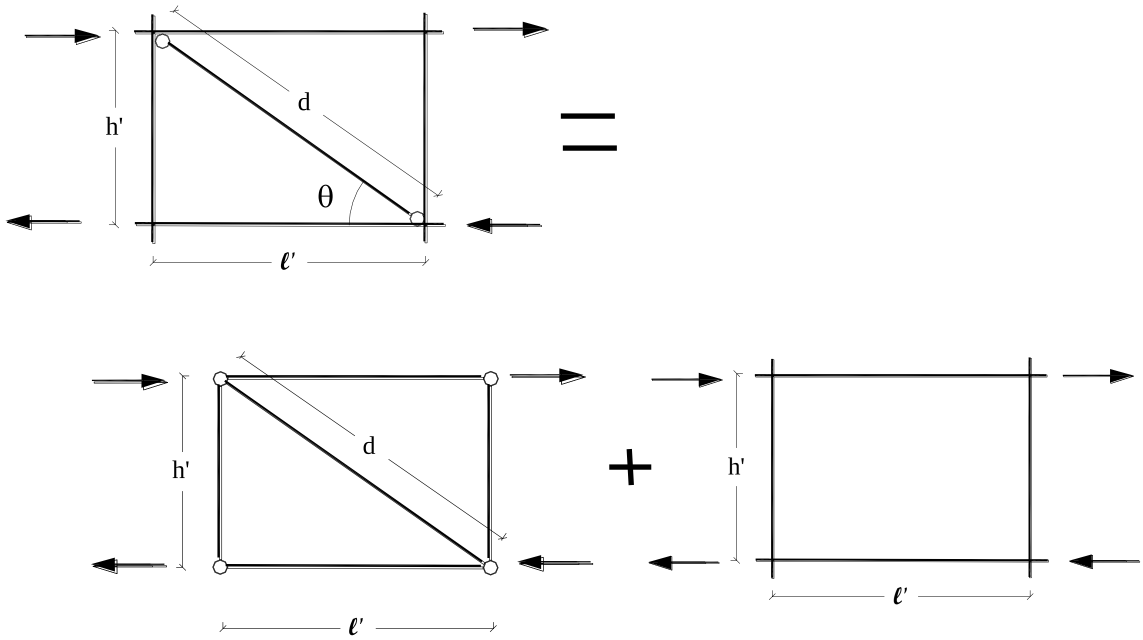


Fig.1 Effect of vertical load on the frame infill contact region under lateral load.



a) b)

Fig.2 An infilled frame under horizontal load: (a) actual system; (b) macro-model.



a)

b) c)

Fig. 3 Decomposition of the macro-model in two schemes

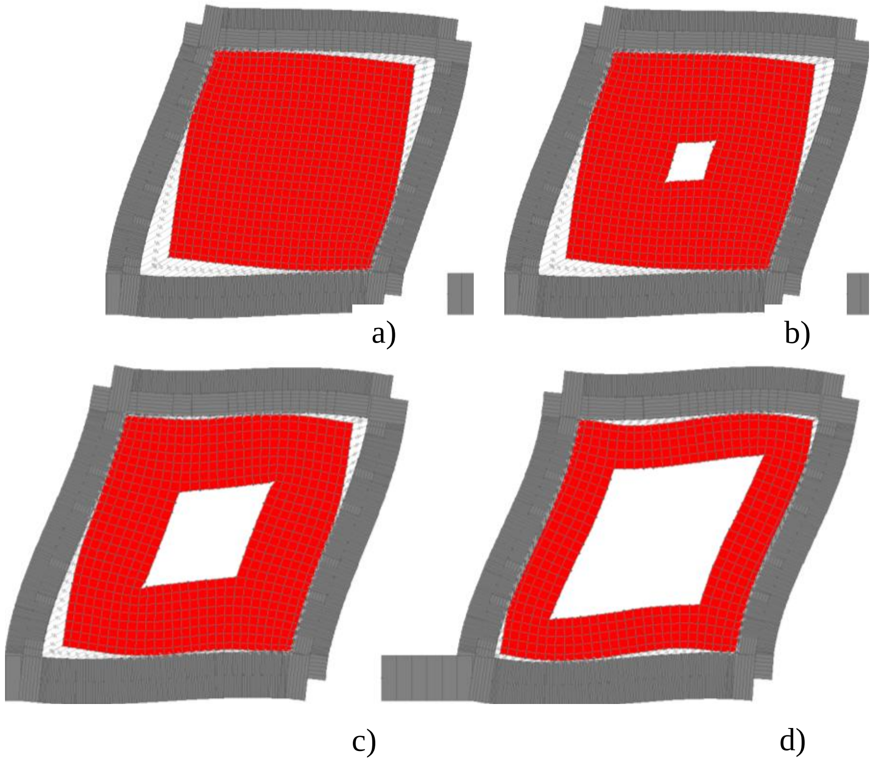
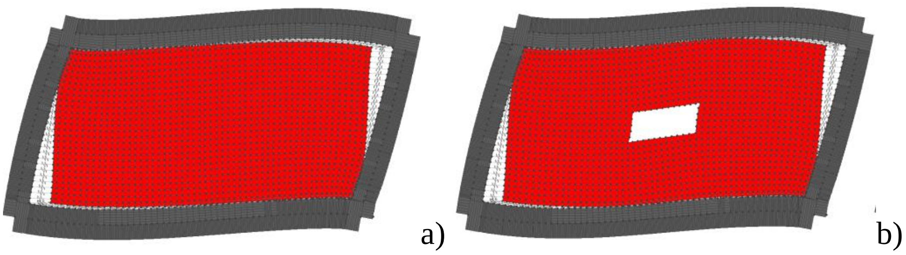
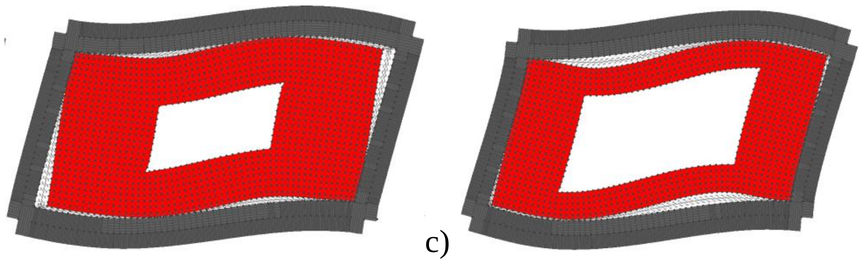


Fig. 4. Qualitative infilled frame deformed shape under lateral load for different opening extensions

- $\frac{\ell}{h} = 1$





c) d)

Fig. 5. Qualitative infilled frame deformed shape under lateral load for different opening extensions

- $\frac{\ell}{h} = 2$

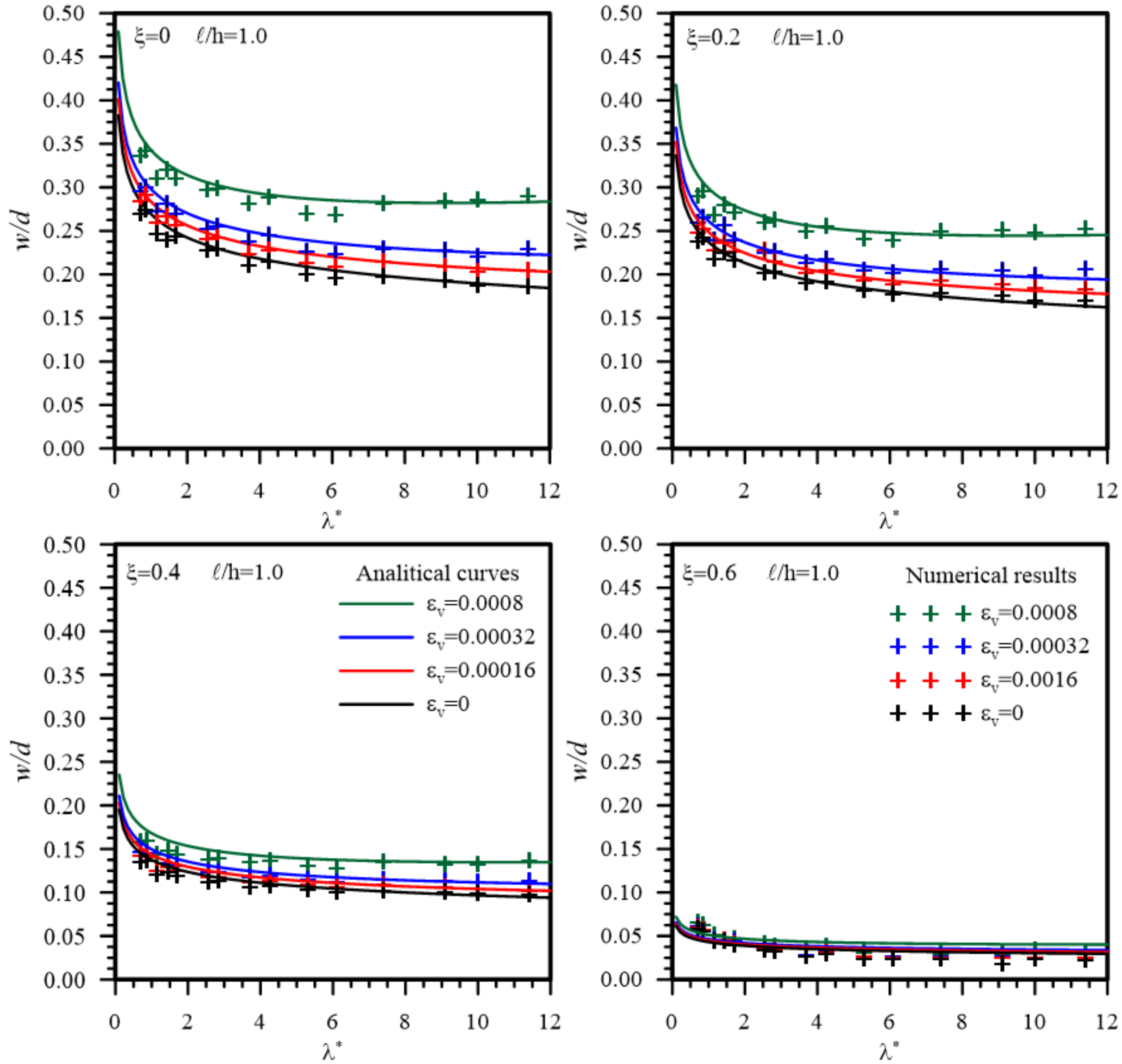


Fig. 6. Values of w/d varying the vertical load and the opening ratio: experimental points and fitting curves – $\frac{\ell}{h} = 1$

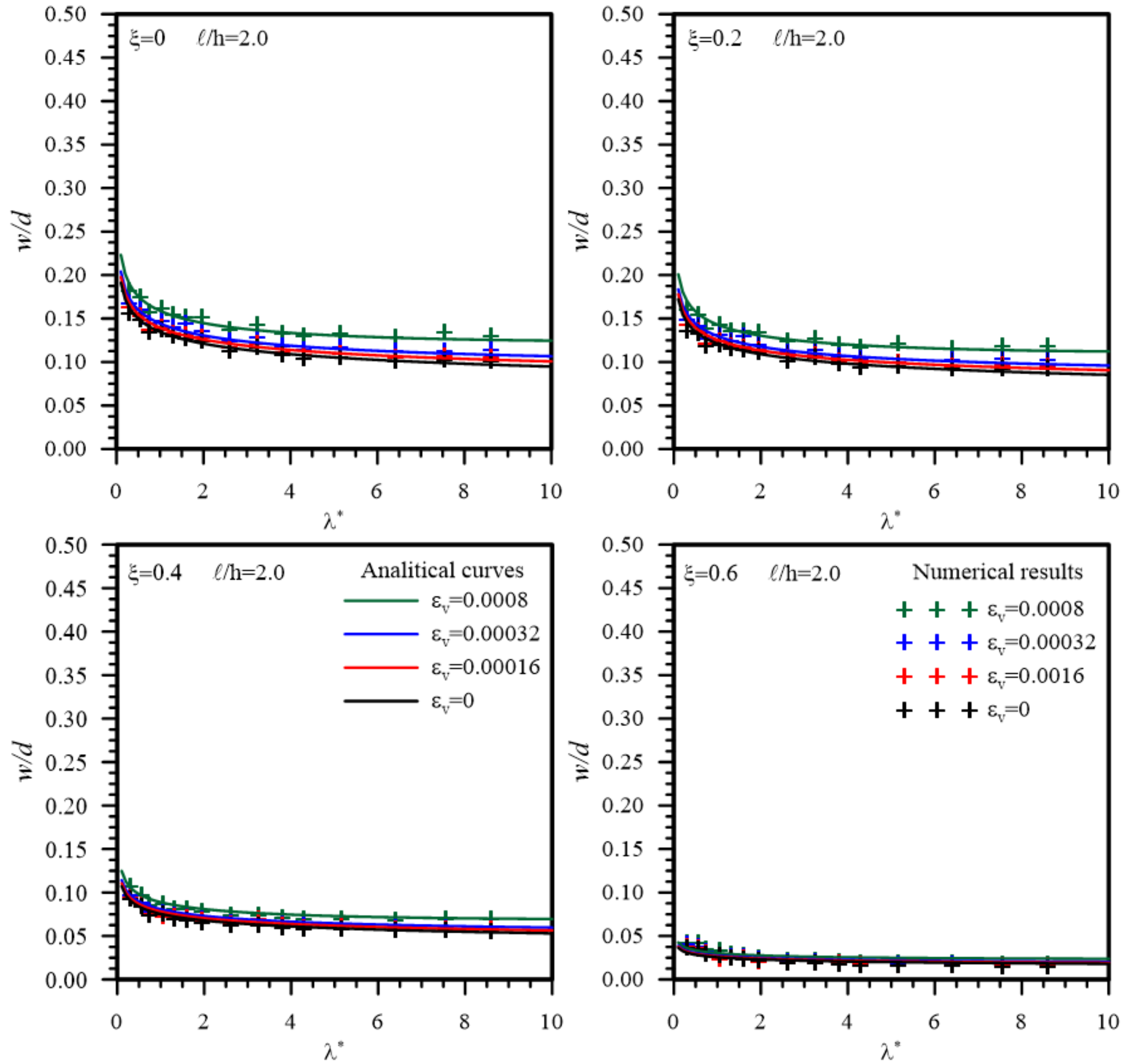


Fig. 7. Values of w/d varying the vertical load and the opening ratio: experimental points and fitting curves - $\frac{\ell}{h} = 2$

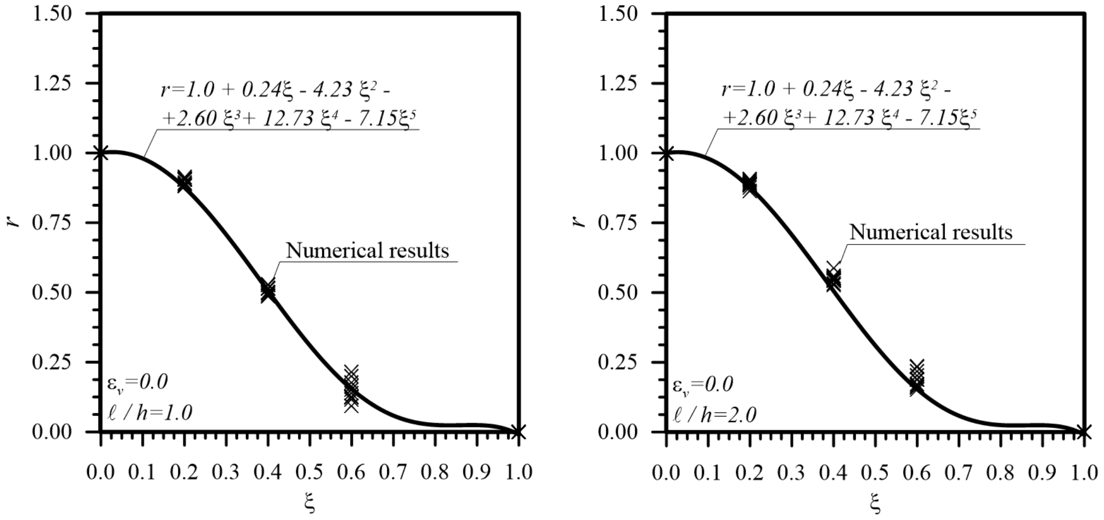


Fig. 8. Reduction factor (numerical points and fitting curve) of the dimensionless strut width (w/d) varying the opening ratio ξ : a) square infills, b) rectangular infills

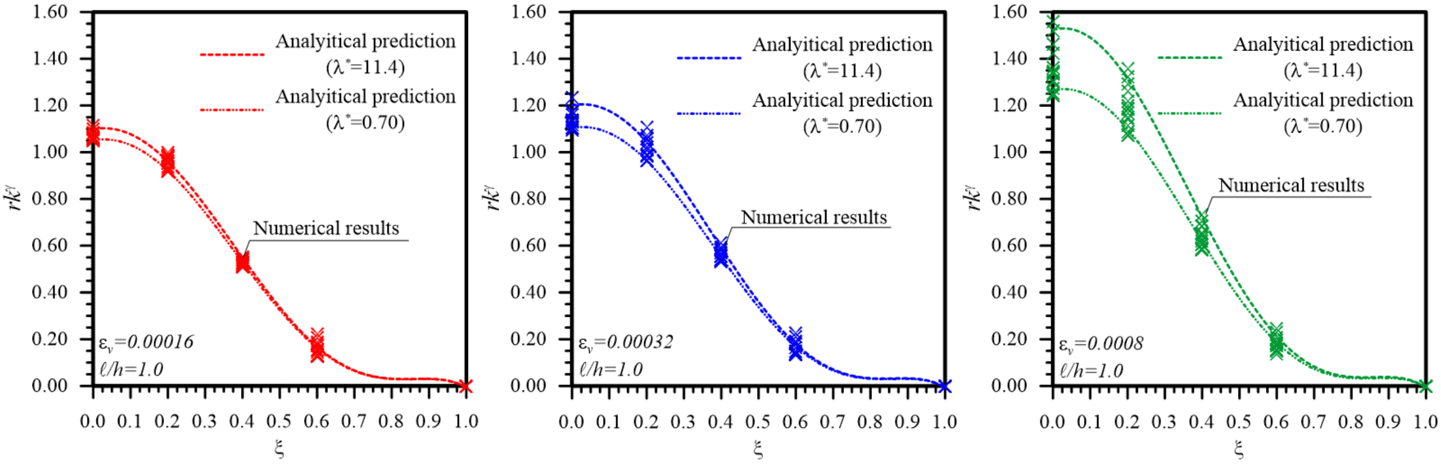


Fig. 9. Reduction factor of w/d due to openings combined with the amplification factor due to vertical loads for different levels of vertical loads (numerical points and fitting curves) - $\frac{\ell}{h}=1$

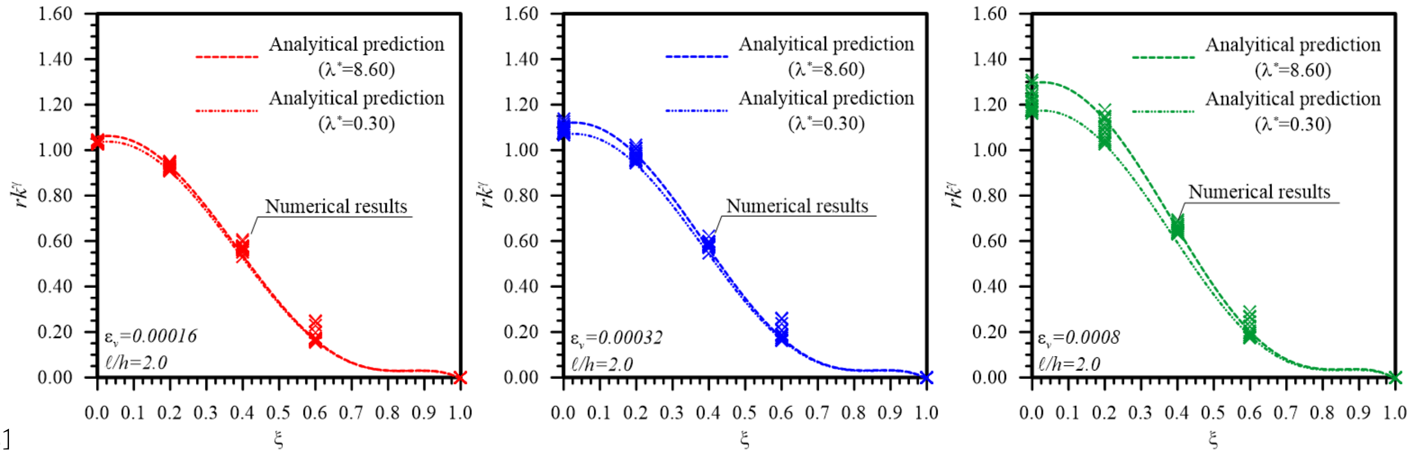


Fig.10. Reduction factor of w/d due to openings combined with the amplification factor due to vertical loads for different levels of vertical loads (numerical points and fitting curves) - $\frac{\ell}{h}=2$

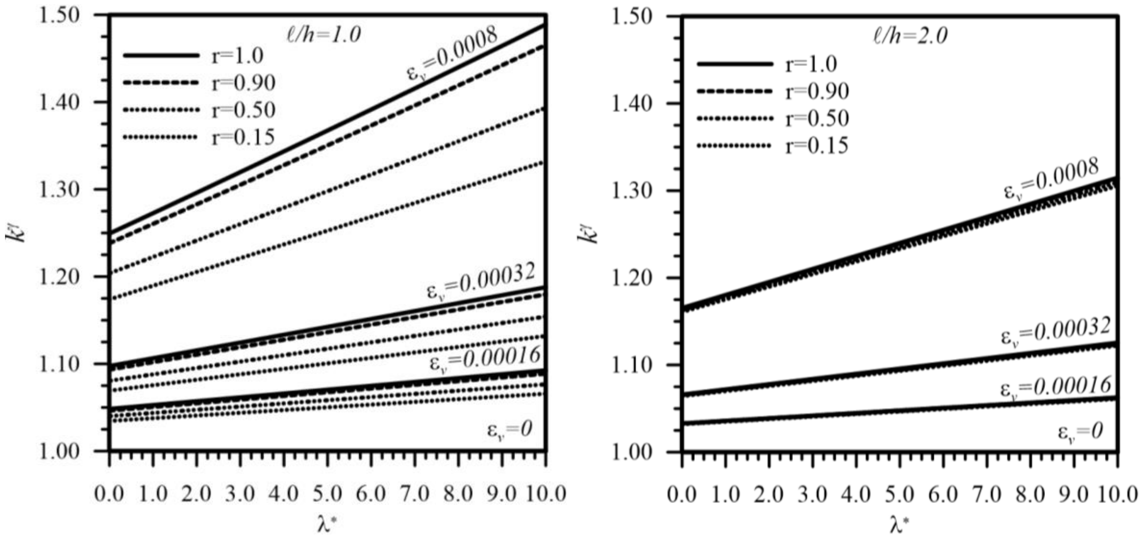


Fig.11. Values assumed by kg varying the aspect ratio, the vertical loads and the opening ratio.

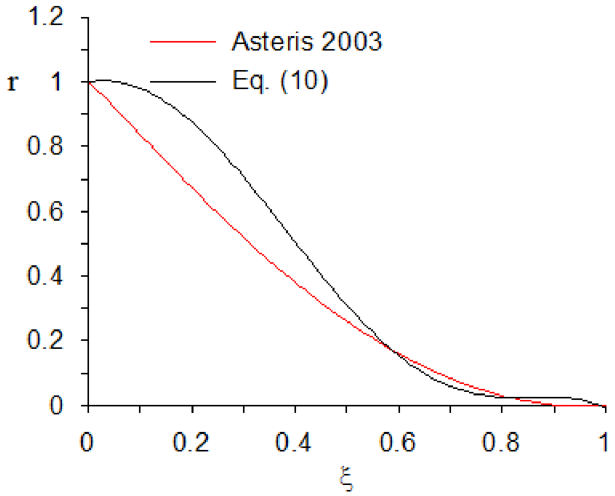


Fig. 12. Comparison between the proposed analytical expression of the reduction factor *r* and the that obtained from Asteris (2003).